LCA Methodology

Predicted Environmental Impact and Expected Occurrence of Actual Environmental Impact

Part II: Spatial Differentiation in Life-Cycle Assessment via the Site-Dependent Characterisation of Environmental Impact from Emissions *(Int.J.LCA 4/1997)*
Part I: The Linear Nature of Environmental Impact from Emissions in Life-Cycle Assessment *(Int.J.LCA 3/1997)*

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Spatial Differentiation in Life-Cycle Assessment via the Site-Dependent Characterisation of Environmental Impact from Emissions

Abstract

Due to a lack of spatial and temporal differentiation in life-cycle assessment (LCA), no environmental concentrations can be predicted. As a consequence, it does not seem possible to evaluate whether a no-effect level is exceeded. Therefore, some LCA studies show a poor relationship between the predicted environmental impact and the expected occurrence of actual environmental impact for impacts of a non-global character. This article discusses possibilities for the inclusion of spatial information in life-cycle impact assessment and provides an outline of a site-dependent approach. The required level of complexity in LCA is analysed. The elements of the cause-effect relationships to be incorporated in characterisation modelling, and the need for spatial and temporal differentiation within each of these elements are discussed. It is argued that the accordance between the impact predicted by LCA and the expected occurrence of actual impact can be improved considerably through the use of a site-dependent approach in impact assessment, and without unacceptable increasing uncertainty. In such an approach, the assessment process is extended with a few general site-parameters.

Keywords: Actual environmental impact; emissions, life-cycle impact assessment; environmental impact, multiple sources; environmental impact, predictec; environmental impact; life-cycle impact assessment; site-dependent approach, life-cycle impact assessment; spatial differentiation, life-cycle impact assessment

1 Introduction

There is an ongoing discussion of whether impact assessment should be a part of life-cycle assessment (LCA). The crux of the debate lies in the limited accordance between the impact predicted by life-cycle impact assessment and the expected occurrence of actual impact (Potting and Hauschild, 1997). Deliberating the pro's and con's, it is our opionion that an LCA without an impact assessment cannot be considered an LCA. However, the spotted lack of accordance seriously affects the credibility of LCA. Enhancement of the impact assessment phase is therefore of vital importance for the credibility of LCA.

We strongly believe that the impact assessment phase can be enhanced as soon as we have a clear understanding and acceptance of the nature of the assessed impact in relation to the specific application domain of LCA. This was the subject of a previous article from Potting and Hauschild (1997) in this journal, and since the present article builds further on this work, some main insights and conclusions are reviewed in Section 2.

The rest of this article sketches the possibilities for inclusion of restricted spatial detail with help of a site-dependent approach in life-cycle impact assessment. Section 3 presents a framework for a systematic description of the levels of detail in well known impact assessment methods. Next, the required levels of detail in LCA are discussed in

Section 4 (cause/effect relationships), Section 5 (temporal detail) and Section 6 (spatial detail). Section 7 proposes an approach to include spatial differentiation by a site-dependent characterisation in LCA. Some main conclusions are drawn in Section 8.

2 The Linear Nature of Environmental Impact

According to Klöpffer (1996), the main problem with life-cycle assessment consists in the absence of true relationships between interventions and environmental effects. The interventions established in the inventory analysis are expressed in amounts per functional unit, and in principle nothing is known about the source-strength and variation over time of the examined processes. Due to this lack of differentiation, which is inherent to LCA, no environmental concentrations can be predicted and, as a consequence, it does not seem possible to evaluate whether a no-effect-level is surpassed. However, Potting and Hauschild (1997) argue that it is possible to say something sensible about the surpassing of no-effect-levels and the expected occurence of actual impact without precise information about the resulting environmental concentration:

The impact from a concentration increase is given by the movement on the concentration/effect curve from the situation without to the situation with an increased concentration (→ *Fig. 1*). The impact size per unit of concentration increase may be put on a par with the slope of the concentration/effect curve and thus be taken as linear, as long as the concentration increase is marginal compared to the "background concentration". This holds true where the "background concentration", that is the situation without concentration increase, reflects the total environmental concentration from many sources together to which the full emission of a single source only contributes marginally. If the full emission from a single source can be regarded as marginally contributing, the same inherently holds true for the emission related to one product unit.

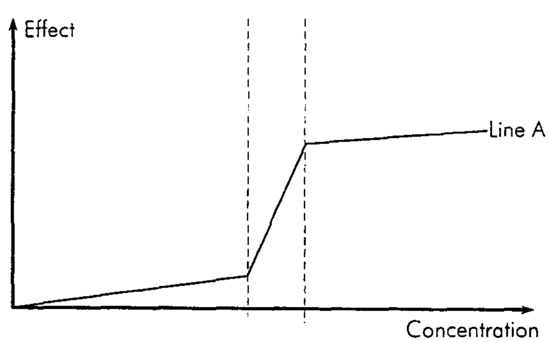

Fig. 1: The shape of a regular concentration/effect curve

The marginality assumption is expected to be justified for the non-local impact categories: eutrophication, acidification, tropospheric ozone creation, stratospheric ozone depletion, increased radiative forcing in global warming, and toxicity from compounds with a long residence time. For impact categories with a local character, the full emission from a single source may often contribute considerably to the concentration in the receiving environment. Here, the source can thus not be regarded as marginal, but it seems fair to assume that the resulting environmental concentrations remain below the no-effect-level due to the process-oriented policy measures. The first section of the sigmoid concentration/effect curve may defensibly be taken as linear.

Initially, environmental legislation was developed predominantly to control and minimise a riskful situation created by a single source. This so-called process oriented environmental policy appeared to be rather ineffective in curbing the environmental problems caused by concentration levels with a multiple source character. In this context, a product oriented environmental policy started to develop, aiming on general pollution prevention ("less is better") rather than on risk minimisation ("only above threshold"). All emissions are relevant in a general prevention of pollution. Nevertheless, a product-oriented environmental policy would also preferably give higher priority to pollution prevention in sensitive areas, than to areas less sensitive for that specific pollutant. LCA should preferably provide sufficient information to allow such differentiation. That is why distribution, exposure and sensitivity of the receiving environment cannot be fully disregarded in LCA. The crucial question, however, is what levels of detail are required for this purpose in characterisation modelling. Before going into this question, it seems useful to set the framework for a systematic description and discussion of these levels of detail in characterisation modelling.

3 Levels of Detail in Characterisation

The required complexity for characterisation modelling in LCA was first discussed at the 1992 SETAC workshop in Sandestin (Fava et al., 1993). Five levels of detail were distinguished here, reflecting the increasing sophistication of the characterisation process. These levels have been intensively discussed ever since (Fava et al., 1994; Udo de Haes et al., 1996), because of the somewhat inconsistent and unclear definition that allows overlapping between some of the levels. A provisional conclusion on this discussion is provided by the recent proposal of a different framework by the SETAC Europe Workgroup on life-cycle Impact Assessment (Udo de Haes et al., 1996):

Udo de Haes et al. (1996) make a distinction between "dimensions of impact information" and "levels of sophistication" within these dimensions. The level of sophistication refers to the degree of detail covered by the characterisation model. The following dimensions of impact information are distinguished: (1) effect information, (2) fate and exposure information, (3) background level information, (4) spatial information. The first and second dimensions directly refer to the links in the cause/effect chain (→ *Fig. 2*). The third and fourth dimension can be considered as additional conditions modifying the processes in the chain. These four dimensions of impact information are seen as relevant for both emissions and depletion of resources (Udo de Haes et al., 1996).

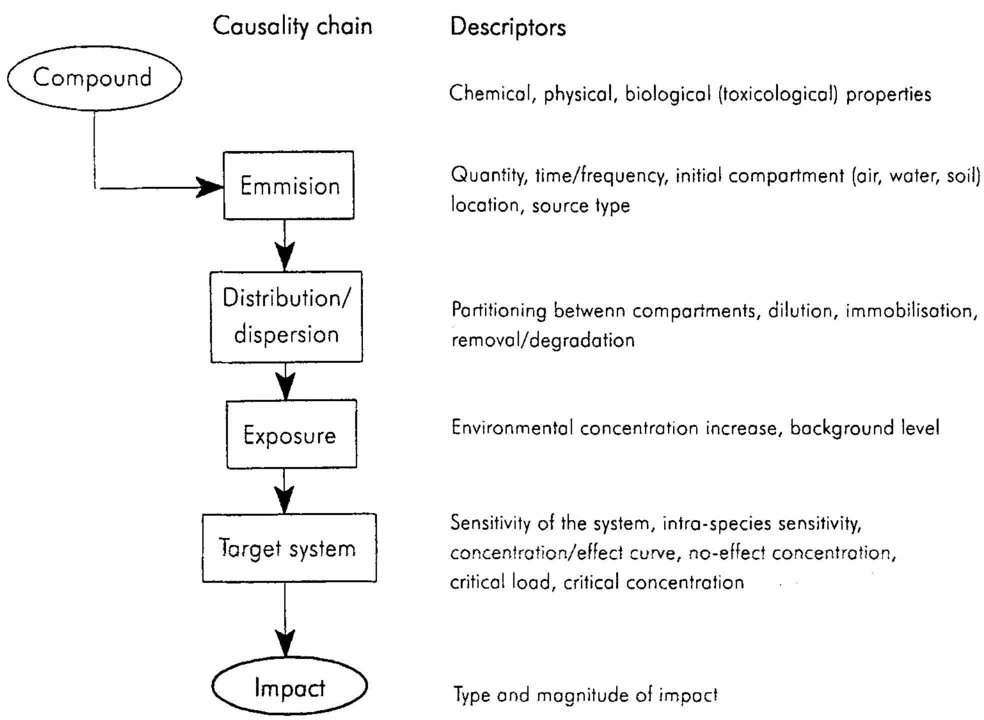

Fig. 2: General cause chain for the environmental impact of an emitted compound (JAGER et al, 1994)

Very clarifying in the proposal of UDO DE HAES et al. (1996) is the distinction between "dimensions of impact information" and "levels of sophistication" within these dimensions. However, we experience the proposed dimensions as confusing. An adaptation of the dimensions of UDO DE HAES et al. (1996) was suggested by POTTING (1996) The framework is presented in **Figure 3**. A similar line of thoughts, although not explicitly formulated in terms of dimensions and levels of sophistication, is followed in the recently published Danish method for LCA (WENZEL et al., 1997; HAUSCHILD and WENZEL, 1997).

The first dimension in **Figure 3** is in accordance with the proposal by UDO DE HAES et al. (1996). The second dimension is almost identical to the second dimension of UDO DE HAES et al. (1996). Only the exposure information has been removed. In this way, all information which is connected to the source is covered by the second dimension (emission, distribution/dispersion, concentration increase). The third dimension comprises the third dimension from UDO DE HAES et al. (1996) and, in addition, all other types of information about the receiving environment and/or target system (background concentration, exposure increase, sensitivity of the target system, etc.).

Within each of the three dimensions, the characterisation modelling addresses different levels of sophistication. The levels of sophistication can be seen in two directions: (1) the extent to which all relevant links (and herein descriptors) of that part of the cause/effect chain are taken into account (see Section 4), (2) the differentiation within each link (or herein descriptors) with regard to modifiers like time (see Section 5) and space (see Section 6).

Differentiation in a higher dimension may put requirements on a lower dimension. For instance, it doesn't make sense to distinguish between different receiving areas if this is not supported by a differentiation in effect information. However,

Dimensions of impact information		Levels of sophistication				
1	effect information	standard	→	NEC	→	slope
2	fate information	none	→	some	→	full
3	target information	none	→	some	→	full

Fig. 3: Dimensions of information and levels of sophistication in life-cycle impact assessment (POTTING, 1996; WENZEL et al., 1997; HAUSCHILD and WENZEL, 1997)

there is neither an overlap between dimensions, nor between the levels of sophistication. The framework proposed by POTTING and HAUSCHILD is expected to have a considerable heuristic power in systematising different methods for assessing environmental impacts in LCA as well as in other contexts (→ *Fig. 4*). This aspect is not further elaborated here.

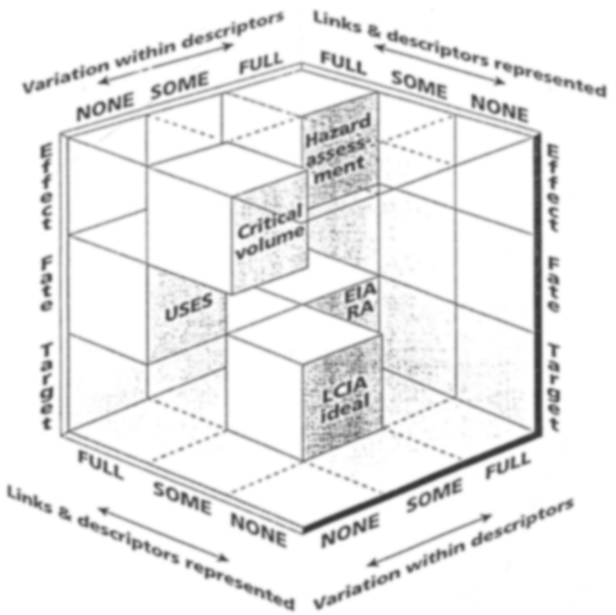

Fig. 4: Different impact assessment methods in general as well as LCA, systematised according to POTTING and HAUSCHILD

The proposal of POTTING and HAUSCHILD can be expressed in a general characterisation formula. This formula is slightly different from the one presented by JOLLIET et al. (1996) to describe the framework from UDO DE HAES et al. (1996). The formula here is already presaged in WENZEL et al. (1997) and HAUSCHILD and WENZEL (1997). The symbols have been adapted to clarify the similarities and differences with JOLLIET et al. (1996):

$$S_i^{nm} = E_i^m * F_i^{nm} * T_i^{nm} * M_i^n$$

Where:

S_i^{nm} = the resulting impact in the final medium (m) from the emission of compound (i)

E_i^m = an effect factor or toxicity reference for compound (i) in the final medium (m) (usually the reciprocal of some kind of NEC); the final medium can be air, water, soil or the food chain

F_i^{nm} = a fate factor for compound (i) emitted to the initial compartment (n) and transferred to the final compartment (m), taking into account emission and distribution/dispersion characteristics (→ *Figs. 2 and 3*); the fate factor represents the proportionality between the emission (M_i^n) and the concentration increase in the final medium (m)

T_i^{nm} = a target factor for compound (i) received in the final compartment (m) or by the target system/organisms, taking into account exposure and target characteristics (→ *Figs. 2 and 3*); the target factor represents the roportionality between the concentration increase in the final medium (m) and the effect variable (S_i)

M_i^n = the emission of compound (i) to the initial medium (n); the initial medium can be air, water or soil

4 Cause/Effect Relationships in Characterisation Modelling

The SETAC-Europe workgroup on life-cycle Impact Assessment has expressed a preference for a detailed characterisation modelling (UDO DE HAES et al., 1996). However, an important group of LCA experts also advocates a less detailed form of characterisation modelling (LINDFORS et al., 1995[a,b]; WENZEL et al., 1997). The discussion between the so-called "full fate" and "some fate" sympathisers has focussed predominantly on the extent to which each link of the chain, and each descriptor within these links, should be included. In our opinion, this depends on the purpose of the impact assessment and the effort that can be put into it.

Figure 2 represents the cause/effect chain that relates an emission of a compound to the impacts that it may cause in the environment. Each link in the chain is described with a set of descriptors that constitute the outcome or importance of that specific link.

For the support of environmental policy directed on controlling processes with well-defined process conditions at well-defined locations, a detailed characterisation like in risk assessment or environmental impact assessment is frequently required. This type of characterisation must cover all links, and operate with a high degree of differentiation within these, in order to provide sufficient relevant information for decision-making. The primary aim of this kind of decision-making is prevention of a riskful pollution situation created by the emission from a given, single source (see also Section 2).

The restricted availability of spatial and temporal information in LCA makes a detailed impact assessment nearly impossible. However, such detailed assessment is not even necessary to provide sufficient relevant information for a product oriented environmental policy. After all, this type of policy is not aimed at risk prevention from a single source, but on pollution prevention (in particular in riskful situations) that result from the emissions from many sources together. Pollution prevention in multiple source situations preferably focusses on the main contributing sources. This requires comparing and prioritising of sources on the basis of their relative importance.

Pollution prevention in a product oriented environmental policy is achieved by (1) stimulating environmentally friendly products at the expense of less benign alternatives (comparing products), or by (2) optimising the life-cycle of specific products (comparing processes within a life-cycle).

For this purpose, full coverage of all descriptors in life-cycle impact assessment is not necessarily relevant. An illustration can be found in the equivalency factors of the IPCC for the aggregation of greenhouse gases:

The residence time in the atmosphere largely influences the contribution from a compound to the increased radiative forcing in global warming. For the same impact category, however, inclusion of the target information does not add relevant information and can therefore be disregarded. After all, the effect of one equivalent unit of greenhouse gases on the oceanic sea-level rise, for example, is always identical, irrespective of the geographical location of the source from which it is emitted, because of global distribution after emission of the relevant compounds.

A link or a descriptor can be left out, and should as a rule not be represented in the impact assessment unless it provides additional information for a more meaningful comparison. A more meaningful comparison means that the resolving power of the characterisation model has to be increased considerably by the incorporation of additional links or descriptors. The inevitable simultaneous introduction of new uncertainties should therefore be in balance with the additional information gained.

Full fate characterisation can be obtained by means of integrated environmental multi-compartment models. However, the presently available full-fate models lead to substantially different results (COWAN et al., 1995). It should be pondered whether the uncertainties introduced by these models are justified by the additional information that is gained. Partial fate (and target) modelling as proposed by WENZEL et al. (1997) or LINDFORS et al. (1995[a,b]) might serve as well without introducing unnecessary uncertainties.

Inclusion of particular links or descriptors can be necessary to allow spatial and/or temporal differentiation. The relevance and possibilities for this kind of differentiation will be the subject of the next sections.

5 Temporal Aspects in Characterisation Modelling

The time aspect plays a role in several phases of the LCA methodology, but the discussion is dominated by what is known among insiders as the flux/pulse problem in characterisation modelling of human and ecotoxicity (ASSIES, 1994[a,b,c]; HEIJUNGS et al., 1994[a,b]; JOLLIET, 1995). As repeatedly brought to attention by ASSIES (1994[a,b,c]), the lack of a time dimension in the inventory data blocks a proper modelling of concentration and exposure.

Besides the magnitude, also the duration of the exposure to a given compound influences the impact on human or ecotoxicity. For some compounds, toxic effects occur after the intake of a certain amount over a short period of time, while the intake of the same amount spread out over a long period causes no toxic impact. Due to the lack of information about the strength and duration of an emission, the duration of an exposure cannot be taken into account in the present life-cycle impact assessment. As a result, the toxicity potential of a polychlorinated biphenyl congener (PCB), delivered to a target over a period that may encompass several decades, is put on a par with the toxicity potential of a similar amount of phenol delivered to that target over a period of a few hours. This equalisation may lead to arbitrary results (ASSIES, 1994[a,b,c]).

Present toxicity characterisation models in LCA usually assume steady-state conditions for the assessed compound in the receiving environment. According to JOLLIET (1995), the pulse/flux issue is no longer relevant as long as steady-state conditions are assumed. With the help of mathematical deduction, he argues that the magnitude of an exposure is proportional to the amount of compound emitted under steady-state conditions. Time characteristics of the emission and subsequently the emission are then no longer relevant according to JOLLIET (1995). This reasoning might be true for steady-state conditions, but it ignores the quintessence of ASSIES' argument. As a matter of fact, although he doesn't phrase it that explicitly, it is precisely the justification of the steady-state he questions.

The assumption of a steady-state, however, has hardly been discussed, not even by ASSIES (1994[a,b,c]). Also ASSIES takes the steady-state as a starting point and looks within this assumption for a solution to overcome the identified problem. He suggests to consider the interventions as continuous fluxes by introduction of the time dimension through adjusting of the functional unit to the yearly production of the examined product. However, as pointed out by HEIJUNGS et al. (1994[a]), HOFSTETTER (1996) and UDO DE HAES et al. (1996), this doesn't solve the problem either. Although one can adjust the functional unit such that one of the processes in the life-cycle is included to its actual extent, the other processes will not fit.

At present, no acceptable solutions for the flux/pulse problem are available. Before putting large efforts into finding solutions, however, it might be a good idea to investigate in what situations the assumption of a steady-state is justified within life-cycle impact assessment. As mentioned in Section 2, the emission of a compound with a long residence time can usually be regarded as contributing to concentration levels that result from many sources together. The marginality of the contribution from a single source to the total implies steady-state conditions. However, the steady-state assumption does not necessarily hold true for compounds with a short residence time. The full emission from a single source can contribute considerably to the concentration in the receiving environment, and the time characteristics (duration and/or frequency) of the emission have a strong influence on this. In contrast with other impact categories, there is an almost infinite number of compounds that are potentially human and/or ecotoxic. The residence time of these compounds can be very different. Compounds with short residence times (with their main impact locally) and compounds with long residence times (having their impact on a larger than local scale) both have their importance in human and ecotoxicity.

Additional to the above discussed issue, there are three other main incentives to consider time aspects in LCA (HOFSTETTER, 1996; UDO DE HAES et al.; 1996): (1) The character and amount of emissions per functional unit are strongly influenced by the level of the applied technologies, which again is determined by the calendar time at which the process is active. (2) The reference calendar time also determines the (estimated) total economic activity and its emissions, and the subsequent environmental concentration levels and impact situation to which the functional unit adds. The contribution from a given source to acidification, for instance, may be very different in 1990 and 2010 due to considerable differences in emission levels from the total economy in those years (POTTING et al., in preparation[a]). (3) The time span on which impact categories are considered, can have considerable influence on the impact size. This may be illustrated with the different time horizons in the increased radiative forcing in global warming, or compounds with a long latency time in human toxicity.

6 Spatial Aspects in Characterisation Modelling

In current life-cycle impact assessment, the potential contributions from the inventory data to each impact category are quantified with generic models. Each impact category is covered by one model, assuming one standard situation for each link in the cause/effect chain (→ *Fig.* 2).

For those types of environmental impact which are of a global nature (like the increased radiative forcing in global warming), the restriction to one standard situation is adequate. Due to their global nature, the contribution to these impact types depends only on the type and amount of compound emitted (see also Section 4). The size of impact can adequately be expressed in terms of an equivalent emission of a reference compound, by multiplying the initial emissions by appropriate equivalency factors (HOUGHTON et al., 1990/1992). However, the restriction to one standard situation is an oversimplification for all impact categories which are not of a global nature.

The concentration increase in the receiving area from an emission varies with the way in which a compound is emitted. For instance, the resulting ground concentration from a stack emission may be negligible due to dilution, while an indoor emission of the same amount of compound will lead to a significant increase of the concentration in the indoor environment. The resulting contribution to human toxicity, for instance, therefore also depends strongly on the source characteristics (like emission height) (POTTING and BLOK, 1994; UDO DE HAES et al.; 1996).

The characteristics of the compartment to which it is emitted, influence the propagation of a compound within the compartment. It is already common practice in LCA to distinguish emissions to air, water and soil. However, a differentiation within one compartment may also be useful. Penetration in the food chain from a given emission will be quite different between agricultural soils, and soils with other functions. Similarly, compounds emitted to sandy soils will leach much faster to groundwater than clay soils. The resulting contribution to environmental impact depends thus on the functions and characteristics of the compartment of emission (GUINÉE et al., 1996).

The impact from a concentration increase is given by the shift on the concentration/effect curve from the situation without to the situation with increased concentration. The impact size thus depends both on the position (background concentration) and the magnitude of this shift. The acidifying impact from a concentration increase in an area with high background concentration is expected to be different from one in an area with low background concentration. At the same time, target systems or receiving areas may have different concentration/effect curves expressing area specific sensitivity towards concentration increases. A calcareous area is relatively unsensitive for acidification compared to a non-calcareous area.

A systematic review of the need for spatial differentiation in LCA for non-global impact categories is given by NICHOLS et al. (1996). A common feature of the examples given above and those from NICHOLS et al. (1996) is that the identified spatial differences can be traced back to the site-characteristics of the source (like source height or geographical location). The site-characteristics of the source roughly presages the spatial differences in characteristics of all links in the cause/effect chain, up to those of the receiving areas (which are also determined by the geographical location of the source).

7 Site-Dependent Assessment

The present restriction to one standard environment in LCA impact assessment is defended with the expected complications in inventory analysis for a more site-specific assessment. For each process in the life-cycle, more site-specific data is required (HEIJUNGS et al., 1992). On the other hand, it is commonly recognized that the predicted contribution to non-global impacts are in poor accordance with the expected occurrence of actual impact in some cases. The elaboration of practical models for inclusion of spatial differentiation into characterisation is identified by the SETAC-Europe workgroup on life-cycle Impact Assessment as one of the main future tasks (UDO DE HAES et al., 1996).

To be feasible and operational in LCA characterisation, the inclusion of spatial differentiation should require minimal additional data. It is our belief that the relevance of life-cycle impact assessment can be enhanced by the inclusion of a few general site-parameters in the assessment process. Such an approach could be called site-dependent.

As shown in **Figure 2**, each link in the cause/effect chain can be characterised by a set of descriptors. The assumption of site-dependent impact assessment is:

1. That it is possible to treat these descriptors as variables with a restricted amount of discrete situations only, and
2. That the influence of these situations can adequately be expressed in terms of an equivalent influence of a reference situation by multiplying the initial emissions by appropriate equivalence factors.

For each impact category, the validity of these two assumptions has to be examined, main descriptors have to be identified and their variation described. A descriptor should only be included in characterization modelling if the relation between the emitted amount of compound and the size of the impact is considerably influenced by spatial variation within that descriptor. For the selected descriptors, the relevant discrete situations have to be defined. For these situations, equivalent factors can be established that express the equivalent influence of a reference situation.

The required types of spatial differentiation within each descriptor will vary for each impact category. Some examples of this have already been given in Section 6. A more systematical review is provided by NICHOLS et al. (1996).

As already mentioned in Section 6, all types of differentiation can directly or indirectly be traced back to the site-characteristics of the source from which the emission comes. The site-characteristics of the source roughly presage the spatial differences in characteristics of all links in the cause/effect chain, up to those of the receiving areas. This means, at the most, that inventory analysis has to be extended with few site-characteristics to allow spatial differentiation. This information is often already directly or indirectly provided by present inventory analysis. As an example, the geographical location of the sources have to be roughly known in order to establish the emissions of transport.

A site-dependent approach to life-cycle impact assessment is expected to combine the benefits of a generic approach with regard to the restricted data requirement and the benefits of a more site-specific approach with regard to the predictive strength of impact assessment (POTTING and BLOK, 1994; UDO DE HAES et al., 1996).

Based on considerations of distribution/dispersion and the situation in the receiving environment, some very practical and simply applicable methods for the site-dependent characterisation of acidification, eutrophication and human toxicity were designed and illustrated with some examples by POTTING and BLOK (1994). The approach in POTTING and BLOK (1994) can be seen as the precursor of the framework presented here. A similar framework is put forward for most impact categories in the Danish method for LCA which has recently been published in English (WENZEL et al., 1997). The elaboration into practical characterisation models, systematically following the framework presented here, will be implemented in the coming update of this Danish work. Factors have already been developed for the site-dependent characterisation of acidification (POTTING et al., in preparation[a]), and are on their way for human toxicity (POTTING et al., in preparation[b]).

Up to now, the attention has mainly been focussed on the spatial differentiation of LCA. The lack of a time dimension in the emission data has dominated the discussion on temporal aspects, and inclusion of this type of information has been strongly discouraged. However, also other types of time-considerations are relevant in LCA (see also Section 5). A characterisation method that allows temporal differentiation in LCA can possibly be designed similar to the site-dependent approach outlined above. Some steps in this direction have already been made by WALZ et al. (1996) by the proposal of a characterisation model for ecotoxicity that integrates spatial and temporal differentiation (by distinguishing between degradable and persistent compounds). Also the already mentioned acidification factors from POTTING et al. (in preparation[a]) anticipate on a time-dependent approach by presenting factors related to the expected emission situation in 1990 and 2010.

8 Conclusions

The information types involved in characterisation modelling can be distinguished into effect information, fate information, and information about the target (or receiving area). Within each of these three dimensions, the characterisation modelling can take different levels of sophistication with regard to: (1) the extent to which all relevant links (and herein descriptors) of the cause/effect chain are taken into account, and (2) the differentiation within each link (or herein descriptors) with regard to modifiers like space and/or time.

The lack of accordance that exists between the predicted environmental impacts by life-cycle impact assessment and the expected occurrence of actual impact seriously affects the credibility of LCA. It is our strong belief that these problems can be overcome by means of a site-dependent approach in life-cycle impact assessment.

In site-dependent assessment, a few general site-parameters are included in the assessment process. Such a site-dependent approach is expected to combine the benefits of a generic approach with regard to the restricted data requirement and the benefits of a more site-specific approach with regard to the predictive strength of impact assessment.

A characterisation method that allows temporal differentiation in LCA, can possibly be designed similar to the site-dependent approach outlined here.

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